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KAON INTERACTIONS WITH VERY LIGHT NUCLEI

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ABSTRACT

Low energy kaon interactions (both K and $\bar{K}$) with very light nuclei are reviewed. Limitations upon present K-nucleus studies due to uncertainties in the K-N amplitudes are emphasized along with promising uses. A brief review of some of the many interesting aspects of $\bar{K}$-nucleus scattering is given. Comparison of the limited K-d and $\bar{K}$-^{4}He elastic data with theory is made. The $\bar{K}d \to \pi\Lambda p$ reaction is discussed including the possible ΣN virtual bound state.

INTRODUCTION

The previous speakers have now thoroughly discussed several topics which might otherwise fall in my purview. Therefore I will forego the usual detailed discussion of K-N and $\bar{K}$-N amplitudes, any consideration of the involved topic of K-mesic atoms, further mention of the stimulating (K^-,π^-) SEX reaction, and serious examination of the related topic of hypernuclear physics. In light of the excellent overview opening this session, I can proceed immediately to the specific points of interest as if you are all experts.

Kaon scattering from light nuclei covers two disparate subjects, since K-N and $\bar{K}$-N amplitudes are not related by crossing symmetry. The K has strangeness +1 and the $\bar{K}$ has strangeness -1. Because historical interest has favored $\bar{K}$ physics, I shall emphasize $\bar{K}$ reactions over K reactions. Also, because of the speculative nature of the field to date, I shall restrict my remarks primarily to those targets for which limited data already exists or appears to be feasible.

Let me once again remind you that it is our hope to use such probes to unravel the mystery of the nucleus. The K and $\bar{K}$ hold promise because of their non-zero strangeness; they do not mediate the N-N force and are therefore not subject to the same overcounting problems as those assiciated with the pion. In a similar vein, study of the associated Y (or Y*) propagation in the nuclear medium may aid in our effort to understand how to treat "Δ propagation" within the nucleus. Clearly our ideas must be put to the test in the very light nuclei, where we have some hope of treating the theory correctly and therefore resolving such questions as what is the proper off-shell amplitude extrapolation, etc.

K-NUCLEUS INTERACTIONS

The K^+ meson is perhaps the more attractive probe of nuclear

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structure. Because of its strangeness, the low-energy KN amplitudes are not resonant--there are no known $S = +1$ baryons. Thus, the K is one of the weakest interacting hadrons, especially when compared to the more usual hadronic probes such as the N, the π, or the α. On the other hand, its interaction is more than electromagnetic. This has led some to propose the K as an ideal probe of the neutron density.[1] (Other possible nuclear structure uses of the K are discussed in Ref. 2-6.) The fact that it is weakly absorbed and therefore "sees" the entire nucleus is certainly an argument that cannot be ignored. However, it is likely that at least the surface features of ρ_n will be determined from proton and pion scattering prior to the existence of extensive K^+-nucleus data.

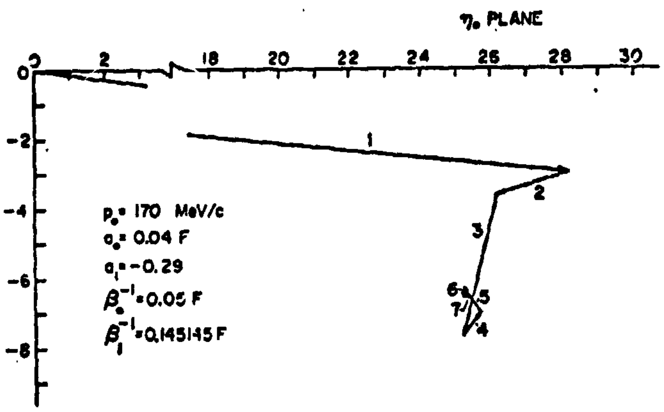
At the present time our knowledge of the K-N interaction is not broad, as we have heard today. The amplitude is elastic below pion production threshold, if one includes charge exchange in the definition of elastic as we do in pion scattering. We know[7] that $\sigma_T \sim 8$-10 mb for $p_{Lab} \leq 600$ MeV/c so that the mean free path of the K is long, being some ~7 fm for a nuclear density assumption of $\sim 1/7\ \mathrm{fm}^{-3}$. For these reasons we expect that i) single scattering is important, perhaps dominant, ii) DWBA might prove to be a good approximation, and iii) K-nucleus scattering should be a volume phenomena. However, the previously published K-N phases[7,8] are in disagreement, and neither the latest K^+p data[9] (a bubble chamber experiment with differential cross sections at 5 points in the range $178 \leq p_{Lab} \leq 580$ MeV/c) nor the companion K^+d data[10] are included in those amplitude analyses.

The $I = 1$ scattering length and effective range from Ref. 9 are $-0.314 \pm .007$ fm and $0.36 \pm .07$ fm respectively. The constructive Coulomb-nuclear interference shows the amplitude to correspond to a repulsive interaction. From Ref. 7 (see also Ref. 1) we find that $\sigma_{I=1} \gg \sigma_{I=0}$ for low energy ($p_{Lab} \leq 300$ MeV/c), so that K^+p dominates; we also know that only $\ell = 0$ is significant in that momentum range. Between 300 and 700 MeV/c laboratory momentum, the cross section contains both $\ell = 0$ and 1; $\sigma^{\ell=1}_{I=0} \gg \sigma^{\ell=1}_{I=1}$ in that momentum range so that K^+n dominates the $\ell = 1$ amplitude. Dover[11] argues that for $p_{Lab} \leq 350$ MeV/c the K will act as a probe similar in nature to the α-particle, except that the α is strongly absorbed. Thus the K may make a better $\Delta S = 0$, $\Delta I = 0$ probe. The changing isospin composition of the K-N amplitude (as a function of p_{Lab}) holds promise of being useful in studying nuclear structure. But as we shall see below, our ability to utilize this probe at present is severely restricted by our inadequate knowledge of the basic KN amplitudes.

The first and only kinematically complete K-d scattering calculation was performed some 15 years ago by Hetherington and Schick. They used a Faddeev type multiple scattering formalism with two-body, S-wave separable potentials of the Yamaguchi form. Coulomb forces as well as $K^+ - K^0$ and other mass differences were neglected. Theoretically they found that in the momentum range of

110-230 MeV/c the impulse approximation was within 25% of the correct answer and that double scattering was good to within 10%. However, for the optical theorem to yield a good result for the total

Fig. 1. Complex scattering amplitude through 7 orders of multiple scattering from Ref. 12.



cross section, triple scattering terms had to be included. (See Fig. 1). A more detailed study was not warranted at the time because of the nature of the available K-N input.

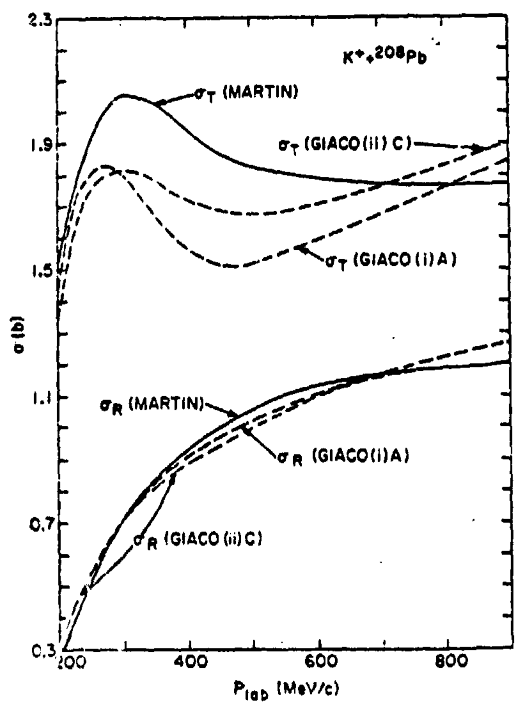


Fig. 2a. Total and reaction cross section predictions from Ref. 1 based upon 3 different KN amplitude sets.

Seeing the elastic scattering studies of Dover and Moffa[1] and the inelastic scattering work of Cotanch,[6,13] it is not clear that the K-N situation has improved. DWBA effects are of the order of 50% in the low momentum region,[13] but more important is that differences between various theoretical predictions with the amplitudes of Ref. 7 and 8 can be just as large or larger,[1,3,13] (See Fig. 2a, b).

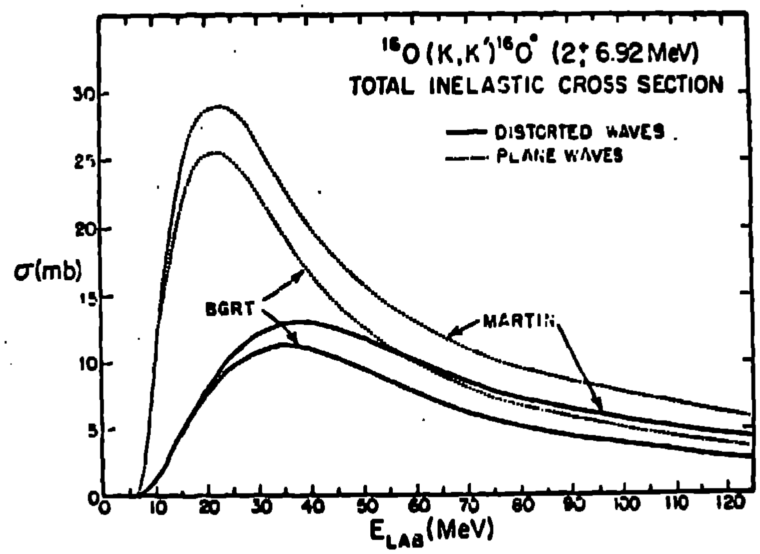


Fig. 2b. Total inelastic cross section predictions from Ref. 13 based upon 2 different KN amplitude sets.

For this reason alone, meaningful K-nucleus analysis will have to await definitive K-N amplitudes. The K^+-d experiments will necessarily be required in combination with K^+-p to determine the K^+-n amplitudes. We have a long row to hoe before we can hope to reap the rewards promised by K-nucleus scattering.

$\bar{K}$-NUCLEUS INTERACTIONS

The $\bar{K}$-nucleus scattering process has proved interesting for several reasons, two of which are:

i) the strength of the $\bar{K}N$ interaction which couples to many resonances, the lowest of which is the $Y^*(1405)$ lying just below threshold.

ii) the strangeness exchange and other reactions which produce hypernuclei of both the Λ and Σ varieties.

The strong nature of the $\bar{K}$-N interaction became evident very early through K-mesic atom studies. The strength was sufficient to make the "scattering lengths" appear to come from a weakly repulsive force if they were incorrectly interpreted in terms of a single-channel potential.[14,15] Along with hypernuclear production one can study coincident γ's;[16] e.g. in the ${}^4_\Lambda He^* \xrightarrow[M1]{} {}^4_\Lambda He$ and ${}^4_\Lambda H^* \xrightarrow[M1]{} {}^4_\Lambda H$ transitions. Thus, one can extract information about excited states of hypernuclei with ($\bar{K}$,γ) just as (π,γ) coincidence measurements yield information about nuclear excitations. The (K^-,γ) reaction has been proposed as a means of studying the Λn interaction[17] as well as the "recoilless" production of hypernuclear states.[18] There exists the possibility of finding Σ-hypernuclear final states which do not convert strongly to Λ-systems; e.g., the reaction $K^- {}^3H \to \pi^+(\Sigma^- nn)$. Finally, the $(\bar{K},K)$ reaction can take us to possible double Λ hypernuclei or exotic cascade (Ξ) hypernuclei, both with $S = -2$. The $K^- {}^6Li \to K^0(\Lambda\Lambda nnpp)$ reaction can lead to the bound,[19] triply-closed shell ${}^{6}_{\Lambda\Lambda}He$. The $K^- {}^4He \to K^+(\Lambda\Lambda nn)$ reaction is not expected to produce a bound $(\Lambda\Lambda nn)$ system (based upon our present scant knowledge of the $\Lambda\Lambda$ force), although the $K^- {}^4He \to K^0(\Lambda\Lambda np)$ reaction might produce a bound ${}^{4}_{\Lambda\Lambda}H$ since ${}^{3}_{\Lambda}H$ is bound. The $K^- {}^4He \to K^+(\Xi^- pnn)$ reaction could result in an exotic bound state, but it will decay rapidly through $\Xi^- p$ conversion; therefore, a more interesting possibility is $K^- {}^3H \to K^+(\Xi^- nn)$.

In the specific $\bar{K}$ scattering and reaction processes that I shall discuss, I will illustrate primarily with deuterium. It is not that heavier systems are uninteresting. It is that out knowledge of the $\bar{K}N$ amplitudes is so poor that even $\bar{K}d$ discussions remain somewhat speculative.

The low energy K-N interaction has been recently summarized by Martin.[20] Therefore, I will only briefly remind you of the salient features. The open channels are

$$I = 0 \left\{ \begin{array}{l} \bar{K}N \to \bar{K}N \\ \quad\;\;\; \to \pi\Sigma \end{array} \right. \qquad I = 1 \left\{ \begin{array}{l} \bar{K}N \to \bar{K}N \\ \quad\;\;\; \to \pi\Sigma \\ \quad\;\;\; \to \pi\Lambda \end{array} \right. .$$

Zero-range K matrix analyses of the low energy data have been published in Ref. 21-23. Effective-range, M matrix analyses[24] have been carried out by Kim[25] and by Berley, et al.[26] Martin[27] has used dispersion relations to constrain the low energy K^-p data analysis in a non-diagonal effective range, M matrix analysis. Since there is no direct information about $\pi Y \to \pi Y$ scattering, the M matrix elements are not uniquely determined. Nevertheless, the $\bar{K}N$ scattering lengths do seem to be well defined:

$$a_0 = -1.66 + i0.75 \text{ fm}$$
$$a_1 = \;\; 0.35 + i0.66 \text{ fm.}$$

Hetherington and Schick have again published the only exact calculation of K^-d scattering including the breakup reaction.[28,29] From their work we can conclude that, up to laboratory momenta of 300 MeV/c, the S-wave is a significant fraction of the total, that there exists significant multiple scattering as in low energy n-d scattering, and that multiple scattering corrections to the total elastic and reaction cross sections are more significant than those in the total cross section due to cancellations. In particular, it is clear that the double scattering terms are an unreliable guide to the importance of multiple scattering (see Fig. 4); i.e., final state rescattering calculations are to be viewed with suspicion.

This was also demonstrated by Myhrer[30] in a model calculation of elastic scattering at zero energy.

The available data for K^-d scattering and reaction processes exist primarily for $p_{Lab} \geqslant 400$ MeV/c.[31] Additional data in this range were reported by Carroll, et al.[32] and compared with previous work. Recently, the model of Ref. 28 was extended to include the hyperon channels implicitly and applied in estimating K^-d elastic and total cross sections.[33] The momenta reached were not large enough to permit confrontation of the data, although the implicit channel approximation is apparently in reasonable agreement with a more complete calculation[34] for these processes. Nevertheless, it

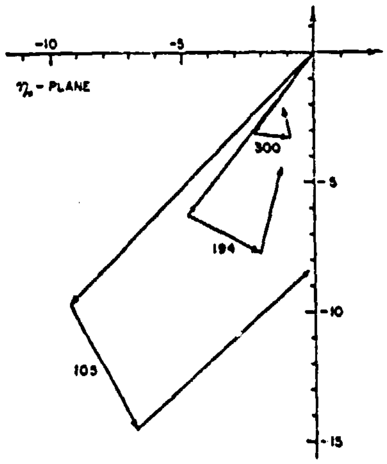


Fig. 4. Contributions to the complex S-wave amplitude for single scattering, double scattering, and full multiple scattering solutions from Ref. 28 for p_{Lab} as indicated.

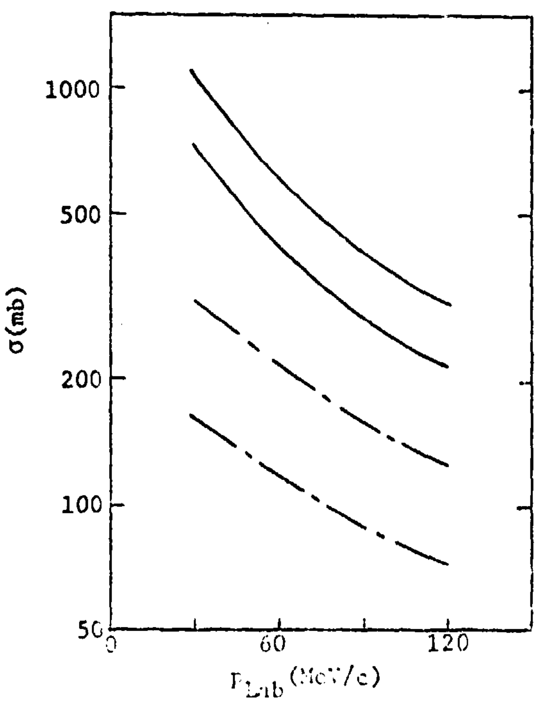


Fig. 5. Comparison of K^-d total (——) and total elastic (— - —) cross sections using the input from Ref. 25 (upper curves) and Ref. 26 (lower curves).

is clear from the numerical results that good $\bar{K}p$ and $\bar{K}d$ experiments at low energy should be a useful aid in differentiating the correct $\bar{K}N$ S-wave amplitudes. (See Fig. 5) The $\bar{K}d$ cross sections predicted using the $\bar{K}N$ input from Ref. 25 and 26 differ by 25-35% throughout the momentum range of 0-120 MeV/c. (One should be cognizant that above 300 MeV/c it is likely more than just S-wave is needed to describe $\bar{K}N$.)

In the Hetherington and Schick charge exchange breakup calculation,[29] results lie a factor of 2 above the sparse data. They did not take into account actual mass differences and charge states, which may explain the overestimate.[35] At least in the elastic scattering calculation,[28] where it is possible to include these effects without an inordinate amount of effort, the difference between the complete and incomplete model calculation is large enough to account for a factor of 2 in the charge exchange reaction, where the cross section is an order of magnitude smaller than the elastic.

Data also exist for the elastic scattering of K^- from ^4He at low momenta.[36,37] In the latter experiment differential cross sections were measured using a bubble chamber at the ZGS by Mazur, et al.[37] in the momentum intervals 100-150 MeV/c and 150-200 MeV/c. They employed a zero-range approximation to extract from the data an S-wave scattering length, a feat not possible in the earlier measurement. Seki claimed some success in fitting the data of Ref. 36 using a multiple scattering formalism and input from Ref. 25. He showed that the real part of the K^-d scattering length in his model agreed with that of Hetherington and Schick, so that one might hope to trust the $K^-{}^4He$ result. However, neglect of the inelastic channels in the intermediate states (meaning that the optical theorem was not satisfied) makes the result difficult to interpret, especially in view of the established importance of multiple scattering through many orders. Deloff and Law[39] then examined the $K^-{}^4He$ elastic scattering problem in some detail obtaining their $\bar{K}$-nucleus potential from folding a $\bar{K}$-N finite range complex potential with the nuclear density distribution. They found a reasonable representation of the data with potentials equivalent to having a 0.4 - 0.5 fm range in a Yukawa model. A comparison of their fit with the data from Ref. 37 and a curve corresponding to the phenomenological potential optical model of Koch and Sternheim[40] is shown in Fig. 6. Reference 39 contains some interesting comments concerning the optical model approach to $\bar{K}$-nucleus low energy scattering, which Deloff continues in Ref. 15. In particular, he points out that the Lorentz-Lorenz effect can give rise to the "change of sign" of the "scattering lengths" from mesic atom data. He also concludes that one must take into account the $\bar{K}N$ finite range--just as in the pion-nucleus optical model, where the zero-range approximation is nonsense.

Let us now turn our attention to the $K^-d \to \pi^-\Lambda p$ reaction. Considerable interest has been generated by the apparent Λp final state enhancement near the ΣN threshold.[41-43] Braun, et al.[44] reported results from a bubble chamber experiment seeming to confirm

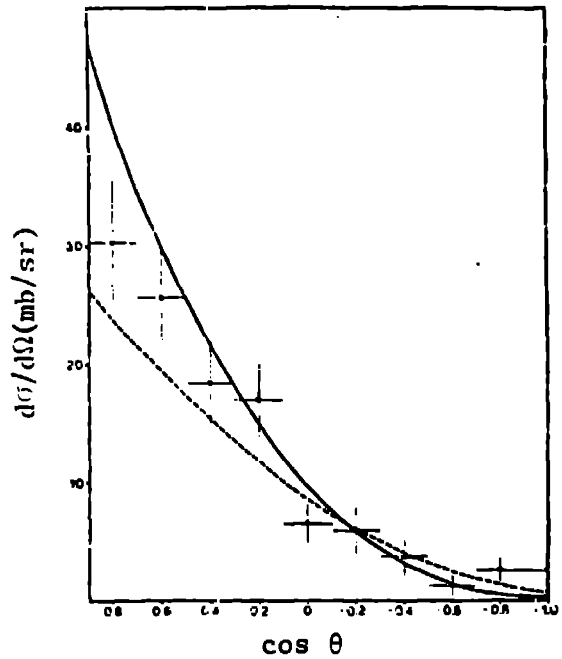


Fig. 6. The $\bar{K}$ - ^4He differential cross section (Ref. 37) for p_{Lab} = 100-150 MeV/c. Solid curve corresponds to Ref. 39; the dashed curve to Ref. 40.

an enhancement in the Λp mass distribution which is interpretable[45] as a ΣN virtual bound state (i.e., the ΣN system would possess a bound state were it not coupled to the Λp continuum). In such a picture, the cross section structure is attributed to $\Sigma N \rightarrow \Lambda p$ conversion. A corresponding analysis of Λp elastic scattering[44,46] also demonstrated the possible existence of a $\Sigma^- p$ virtual bound state contribution to the cross section within the limits set by the data.

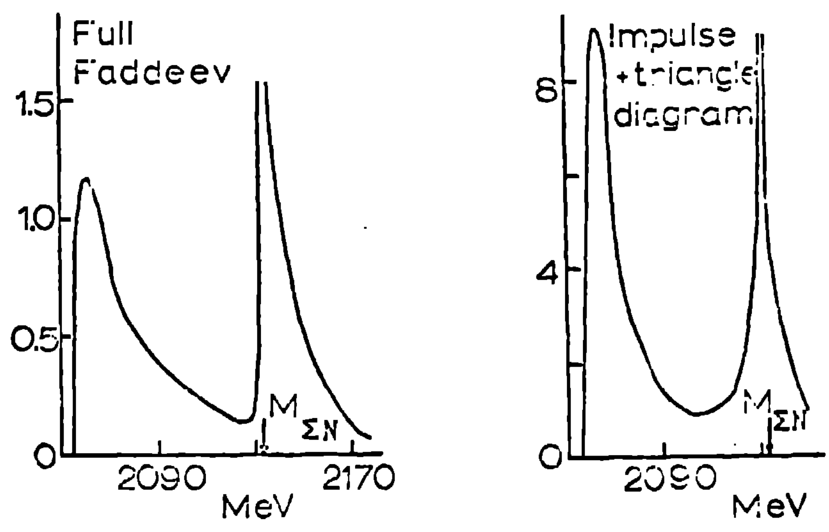


Fig. 7. The model $\bar{K}d \rightarrow \pi\Lambda p$ spectrum as reported in Ref. 47.

In order to understand the reaction, Toker et al.[34,47] have undertaken the very ambitious task of carrying out a complete Faddeev calculation for the coupled "3-body" system $\{\bar{K}d, \bar{K}NN, \pi YN\}$ including the proper matrix representations of the $(\Lambda N-\Sigma N)$, $(\bar{K}N-\pi\Sigma)_{I=0}$, and $(\bar{K}N-\pi\Sigma-\pi\Sigma)_{I=1}$ 2-body interactions. The report of their preliminary results at this conference[47] shows that the various rescattering processes in a Faddeev calculation substantially modify the spectrum from the naive impulse-plus-triangle-diagram estimate (see Fig. 7). No comparison with the data is yet warranted, but the authors are to be commended for their efforts.

Let me close this subject with these comments: Kisslinger has looked at applying symmetry arguments to the OBE potentials (as has been done to predict $\bar{N}N$ potentials) and concluded that there is no ΣN virtual bound state.[48] I would suggest that we seek an answer from the YN coupled potentials of Nagels, Rijken, and deSwart;[49] i. e., does the ΣN channel (without coupling to the ΛN channel) support a bound state? If not, is there a strong virtual antibound state as in the case of the np singlet? I remind you that in the nd → nnp reaction the $(np)_{S=0}$ final state interaction contributes much more to the peak in the spectrum than does the $(np)_{S=1}$.

THE OUTLOOK

It is our fervent hope that the next few years will bring some clarification of the rather murky picture that we see of both the KN and $\bar{K}N$ low energy amplitudes. Certainly the time is ripe for more precise low energy scattering experiments involving the proton and the deuteron. Without that data, the promise held out for the K as a nuclear structure probe will go unrealized, and our understanding of the interesting $\bar{K}$ reactions will remain speculation.

I have not meant to imply that only the K^+ and K^- data are to be sought. In fact, $\bar{K}_0d$ experiments are to be encouraged due to the absence of Coulomb effects which can be large in low energy elastic scattering. One would also be anxious to see kaon scattering from A = 3 and 4 targets, where we think we understand the nuclei and very useful experiments have been carried out with pions. The question of $\bar{K}$ absorption has not really even been addressed, and yet it must be an important open channel which must be considered.

Our ideas about kaon-nucleus interactions are not far from primative. It is in the very light nuclei that they are apt to be most severely tested. The time has come to begin that testing.

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